

On Light-Sensations and the Theory of Forced Vibrations.

By GEORGE J. BURCH, M.A., D.Sc. Oxon, F.R.S.

(Received April 19,—Read June 26, 1913.)

Every hypothesis, whether mechanical, photo-chemical, or ionic, concerning the connection between the light-waves and the sensations they evoke, must of necessity rest ultimately on the theory of forced vibrations. It seemed probable, therefore, that a model illustrating the production of forced vibrations over a range comparable with that of a light-sensation might be of service for teaching purposes, and might prove suggestive in studying the phenomena of vision.

The apparatus now described was made for me in May, 1909, by Mr. H. Davis, the Assistant for Manual Instruction at University College, Reading, and was used in my lectures both in Reading and in Oxford, but no account of it has been published. From a light wooden bar, A (fig. 1), pivoted at the two ends, hang a number of grey silk ribbons, varying in length from 11 to 44 cm. The longest, which represent the red end of the spectrum, have therefore a period twice as long as that of the shortest, which correspond to violet. Each ribbon is weighted at the end with a strip of lead.

The red sensation is represented by a scarlet ribbon occupying the

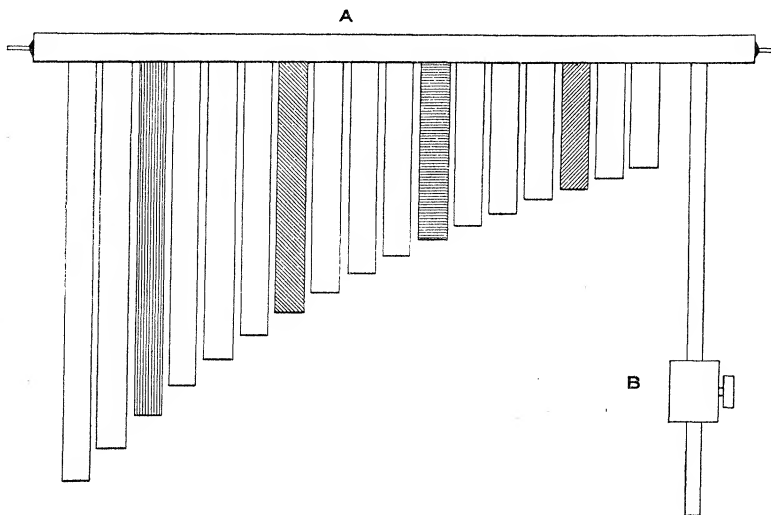


Fig. 1

Side Elevation of Oscillating Bar A, with Silk Ribbons of different lengths acting as Resonators to the Pendulum with Movable Weight B.

position corresponding to Fraunhofer's C-line, the green sensation by a green ribbon near the Fraunhofer *b*-line, and similarly the blue and the violet by a ribbon of each colour in the corresponding region of the spectrum. In the actual model there are five grey ribbons between every two coloured ones—in the diagram only three are drawn, for clearness. The bar A is made to oscillate by a heavy pendulum B, with a movable bob fixed by a thumb-screw. If this is tuned to the period of the green ribbon, although those on either side respond more or less, the maximum amplitude is attained by the green, which, according to the theory of Thomas Young, is most strongly excited by light of a certain wave-length.

If the pendulum is tuned for the yellow, then the grey ribbon underneath the yellow portion of the bar indicates by the amplitude of its oscillation the position in the spectrum of the impressed vibration, while the red and green, representing the colour-sensations, swing moderately, being both, as Young said, excited, though to a less degree, by yellow light. It makes the experiment more striking if the bar A is painted with the complete series of spectral colours, and the principal Fraunhofer lines marked upon it in black in their proper positions.

For some reason, perhaps connected with the fact that the ribbons swing so near each other and that eddies are formed by their edges, friction is relatively greater at small than at large amplitudes, so that to some extent the effect of its increase on the range of resonance may be seen as the oscillations subside. For greater differences I use a set of oscillators with lighter weights.

For purposes of demonstration it is necessary to show the effect upon such a system of resonators of light of more than one wave-length. To do this two heavy pendulums, C and D (fig. 2), are connected by light wooden rods, E and F, to the ends of the cross-link G, from the middle of which a third rod H leads to a crank-pin on the bar A. The heavy bob of the pendulum B being removed, the stem of it, which is quite light, serves as an index to show the compound nature of the motion imparted to the bar A, the movements of which often appear strikingly irregular. But each pendulum is responded to by the resonators in tune with it, as though the others were still.

Quite apart from any theories of colour-vision, the apparatus demonstrates in a striking manner the phenomena of forced vibrations. The change of phase according as the natural period is greater or less than that of the impressed force is well shown, and it is particularly instructive to start with a considerable difference of period between the pendulums C and D, and gradually bring them into unison.

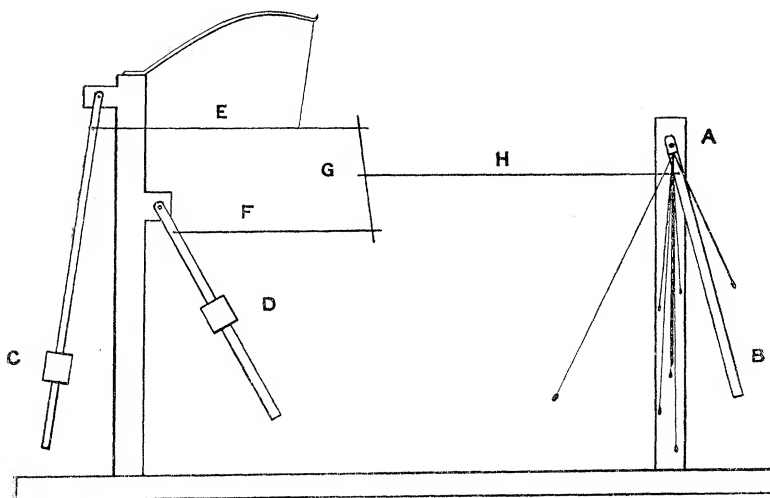


Fig. 2

End Elevation of Oscillating Bar A, showing its connection, by the link-work, E, F, G, H, with the Pendulums C and D, the two Resonators in tune with which are oscillating violently, and the rest scarcely at all.

The periodic variations of amplitude in the response which die out after the impressed force has been in action for a little while are easily seen, and, in fact, the apparatus affords an excellent illustration of §47 and §48 in Volume 1 of Rayleigh 'On Sound.'

For my present purpose the main interest of the apparatus lies in the possibility of utilising it to elucidate one of the most difficult problems of colour-vision—the problem, namely, of white light.

Newton's discovery of the physical fact that the prism separates the beam into rays of different refrangibilities and different colours affords no explanation of the physiological fact that any one of these colours, even the most brilliant, should disappear with absolute completeness in presence of the others. Hering's theory of the antagonism of red and green, and of blue and yellow, is, from this point of view, a most natural one. It would be simple enough, on Young's theory, to explain why all colours tend to white by very strong light, for each of his three hypothetical "nerves" is assumed to be affected, though to a different degree, by light of all wave-lengths, so that we have only to suppose that, with a sufficiently strong stimulus, all three "nerves" are almost equally excited. But this leaves us without any valid explanation of that other fact, that by very feeble light all colours tend to grey.

In some respects the phenomenon of colour is more striking than that of whiteness, and probably, if it had been possible for the spectroscope to be invented before any theories on the subject were thought of, the problem would have rather been to explain why, with a certain intensity of illumination, light of different wave-lengths should appear brilliantly and variously coloured, whereas with less light or with more the colours fade.

The existence of this optimum intensity for the excitation of the sense of colour is very noticeable when calibrating an ordinary students' spectroscope with the Fraunhofer lines by direct sunlight. The act of measuring produces sufficient fatigue to make the spectrum appear pale. If now the instrument is directed towards the sky or a cloud, the colours instantly become rich and brilliant, though it may be necessary to open the slit wider before there is light enough to see them.

I propose to show how this entire range of phenomena—from the scarcely visible band by feeble light to the brilliantly coloured spectrum with optimum intensity, and the washed-out colour with bright sunlight—is in strict accordance with the laws of forced vibrations.

It is, of course, understood that any hypothesis as to the manner in which the ethereal vibrations we think of as light give rise to the sensations we know as light would naturally be expressed, in the first place, in terms of the electromagnetic theory. Inasmuch, however, as the same laws apply to all kinds of harmonic oscillations, whether electrical or mechanical, it will be more convenient to retain the phraseology proper to the mechanical model.

Evidently, the action, whatever it be, must take place through those processes which we commonly regard as chemical—processes, namely, in which some rearrangement of atoms, either within the molecule or from some other molecule, is brought about.

There is a very clear statement by Kühne of the Opto-chemical Hypothesis in Hermann's '*Handbuch der Physiologie*,' vol. 3, p. 327. According to him, the opto-chemical hypothesis regards the visual cells as carriers of chemically decomposable materials called visual substances, which, however, have no effect upon the visual cells as long as they are undecomposed. But the hypothesis ascribes to the decomposition products resulting from the action of light on these substances the power of chemically exciting the protoplasm of the visual cells.

This excitation might conceivably result from the act of decomposition by light of the visual substances, but inasmuch as the effects do not instantly cease with the removal of the stimulus, it would appear that the cause is to be sought rather in the material action of the decomposition products.

In applying to this theory the elementary principles of chemical dynamics,

we must carefully separate the initial electro-chemical action from the resultant physiological action. The production of the active decomposition products which excite the retina takes place, doubtless, according to formulæ capable of exact and more or less simple numerical expression. The regeneration of the sensitive material, whether due to a natural tendency to revert to its original condition or whether effected, as seems more probable, by processes of metabolism, is still conceivably capable of numerical expression. But between these actions, which may be classed as electro-chemical, and the resultant sensation there is a whole group of modifying causes, which must, for the present, be kept outside our attempts at analysis.

There arises, in this connection, a question of general interest in physiology that has not, so far as I know, been fully dealt with. Is the excitation of a tissue by a chemical compound a process of the same character as a chemical reaction? I do not refer to such crude foreign substances as dehydrate or coagulate, or otherwise damage the tissue, but such as excite quite normally its characteristic functions. There must be some end to the activity of the exciting substances in the eye, else, once separated, they would go on exciting sensation indefinitely. Either they recombine or are washed away or their energy is transformed into that of the sensation. I do not attempt to decide this problem, but have so stated the theory that it would not be affected by it.

I. *Opto-chemical Processes.*

Let n = the number of molecules of the visual substance not yet acted on by light.

x = the number of molecules of the decomposition products capable of exciting the retina.

e = the number of molecules of decomposition products used in producing sensation.

The known data are insufficient for a complete statement of the problem—for instance, it would be necessary to know whether any molecules of x remain ultimately unaccounted for by e —whether they are neutralised, destroyed, or simply washed away by the circulation and dispersed.

For our present purpose it is sufficient to note that each of the variables is subject to conditions of equilibrium governed by the ordinary laws.

Then dn/dt = the rate of supply of the visual substance,

and dx/dt = the rate of demand upon it.

Also de/dt = the *physical* intensity of the excitation.

If dn/dt is greater than dx/dt the store n of molecules capable of being

acted on by light increases, and we have, when dx/dt is zero or very small, the condition of dark-adaptation, in which n reaches its maximum.

In the dark-adapted eye we must regard the compound in which the forced vibration is produced, as in a state of maximum concentration, and by all the analogies of electro-chemical action, this must correspond with increased resistance, or, in the mechanical model, with increased friction.

In order therefore to obtain a graphic representation of the meaning of dark-adaptation, we may compare together a series of curves of forced vibrations with different values of the coefficient of friction.

Let it be assumed that the quantity of the exciting substance set free from the sensitive material may be taken as corresponding to the kinetic energy of the forced vibration induced by the action of the light, the expression for which is

$$B = \frac{1}{\Delta^2 + 4k^2}, \quad \text{where} \quad \Delta = \frac{n^2 - p^2}{n} = \left(\frac{n}{p} - \frac{p}{n}\right)p,$$

p being the natural period of the resonator, n that of the impressed force, and k representing friction.*

The ratio p/n corresponds to the musical interval between the natural period of the resonator and that of the forced vibration, and as the expression for Δ is symmetrical with regard to the ratio n/p it follows that if values of B are taken as ordinates and ratios n/p as abscissæ, we shall have for each value of p a curve symmetrical about its apex.

This consideration naturally suggests plotting the spectrum by what may be called the "keyboard" system, in which, as in the piano, equal horizontal distances correspond to equal musical intervals. Except in general illustration of the relation between ultra-violet and infra-red rays I do not think this method has been used. It seems to offer certain advantages in dealing with problems of colour-sensation.

Fig. 3 shows four hypothetical colour-sensation curves plotted on this

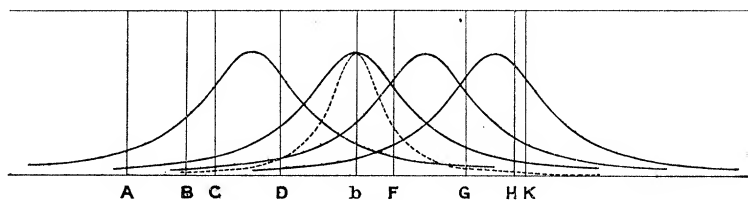


FIG. 3.

Resonance Curves of the Colour Sensations Red, Green, Blue, and Violet, with the coefficient of friction, $k = 0.2$. For the dotted curve $k = 0.1$, but the ordinates are reduced to one-quarter of their full value by the shunt factor.

* Barton, 'Handbook on Sound,' p. 145.

system. They represent the four colour-sensations described in my paper on "Artificial Temporary Colour-Blindness."*

Inasmuch as according to the theory these curves must be symmetrical, I assumed the apex of the green sensation to lie midway between the two ends of it, and similarly with the blue sensation. Then that part of the yellow where neither red nor green predominates must be where the tangents to the two curves are equal and opposite. In this way I got a position for the apex of the red sensation, and in like manner for the violet sensation by means of the blue. It may serve to fix our ideas if I refer to the illustration of the musical scale. Taking E as the apex of red, green would be approximately at G, blue at A, and violet at B.

It is noteworthy that green, blue, and violet are practically equidistant and much closer together than red and green—red in fact might almost be taken to correspond with Eb.

In order to assign a value to the coefficient of friction I was guided by the keyboard interval over which the forced vibration must extend. After a number of trials I decided to take $4k^2 = 0.16$ as a trial value, giving each of the four colour-sensations the same coefficient of friction.

It will be observed that the transition from blue to violet occurs at G, that from green to blue at F, and that from red to green a little above the D line—or exactly at the D line if the centre of the red is placed at Eb. In this case, too, the red would meet the blue about the b line, as it does during artificial green-blindness.

Fig. 4 shows the effect of increasing $4k^2$ to 0.60. Each one of the curves is lower, but it extends over a greater range of wave-lengths in proportion to its height. This agrees perfectly with the well-known fact that "by feeble light all colours tend to grey."

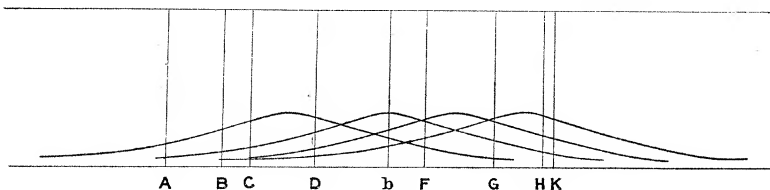


FIG. 4.

Resonance Curves of the Colour Sensations Red, Green, Blue, and Violet, with the coefficient of friction, $k = 0.4$ nearly, i.e. $4k^2 = 0.60$.

In my paper on "Colour-Vision by Very Weak Light"† I have noted the changes which occur in such cases between the boundaries of the colour-

* 'Phil. Trans.,' B, vol. 191, pp. 1-34.

† 'Roy. Soc. Proc.,' 1905, B, vol. 76, p. 214.

sensations owing to the fact that they are not all affected in the same proportion, and also the general effect of the increased extent in the spectrum of the several colour-sensations. "The colour must look pale under feeble illumination owing to the presence of three if not of all the constituents of white."

If this view is correct it would explain a rather puzzling fact that I have noted in my investigation of cases of colour-blindness.* I found it necessary to specify not only those cases in which a colour-sensation was deficient, but those also in which it was of greater extent than usual. The Swiss girl therein referred to had practically but one colour-sensation, because her green so greatly exceeded the normal in spectral extent, yet by suitable fatigue it could be reduced so as to reveal her possession of the other sensations. We have only to suppose that the supply of sensitive material to the green end-organs was so copious as to cause a quite unusual concentration, with correspondingly large coefficient of friction. In such a case the eye would be with respect to green in a condition of dark-adaptation, with this difference, that no ordinary demand could overtake the supply and reduce the store, n , of molecules of visual substance to the normal amount.

In other words $dn/dt - dx/dt$ was positive for all ordinary values of dx/dt .

But it is clear that this might arise either from dn/dt being large, or from dx/dt being abnormally small.

I consider that I have met with cases of both kinds. In one, of which I shall give a full account in my next paper on "Cases of Colour-Blindness," there was monochromatic vision in one eye only. This enabled me to ascertain that the sensation was unmistakeably one of whiteness, with a little colour at the two ends of the spectrum. But the whole intensity of the light-sensation was extremely low although the transparent tissues were perfectly clear.

In the same way we may explain the fact noted in my paper on "Artificial Temporary Colour-Blindness"† that with some people the "overlaps" of the colour-sensations are very large, and with others almost non-existent, and also that with some the overlaps are large between red and green and small at the other end of the spectrum, so that to them yellow is an important colour, and with others there is little or no overlap between red and green, and large overlaps in the green, blue, and violet region. It seems to indicate that the coefficient of friction is constitutionally large in these people either for all the colours or for those to which the large overlaps belong. And by the expression "constitutionally large," I mean large not because any temporary cessation of the demand dx/dt for the exciting molecules has allowed a large

* 'Phil. Trans.,' B, vol. 199, pp. 239 and 250.

† 'Phil. Trans.,' 1899, B, vol. 191, p. 1.

store, n , of visual substances to collect, but because the metabolism is so active that the rate of supply dn/dt of the visual substance is greater than in most people. In quite a number the rate of supply of the visual substance for the blue is so great that it is not recognised as a separate sensation, but confused with violet.

According to this hypothesis, the store n of molecules of the visual substance would be governed by an equation of equilibrium between the causes tending to use, destroy, or disperse the exciting molecules, and those by which they are formed, so that it would have a definite value for every constant intensity of illumination and of physiological condition. In ordinary dark-adaptation we should therefore have a large accumulation n of molecules of the visual substance, so that on coming into a quite moderate light the rate of formation of exciting molecules dx/dt may for a short time be greatly in excess of its ordinary value for that degree of illumination, producing a sensation vividly described by the French word *éblouissement*.*

This gradually passes off as the store n falls to its equilibrium value for that rate of demand dx/dt , when the eye reaches its new condition of adaptation, the curves of the colour-sensations changing into those belonging to the coefficient of friction proper to the concentration represented by the new value of n .

As the intensity of the light increases the equilibrium value of n grows less—the resonance becomes more free and the curves grow peaked, so that a condition is reached represented by fig. 5. Each colour is brilliantly distinct and separated from the rest, dominating its own region of the spectrum. This is the optimum intensity for the excitation of the sense of colour. What happens when the light is still brighter will be described in the next section.

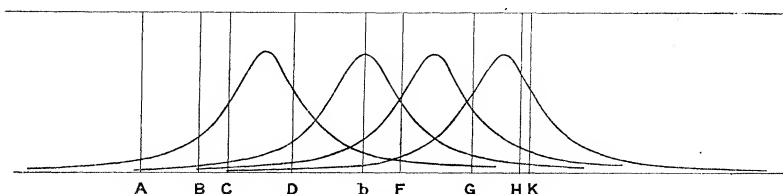


FIG. 5.

Resonance Curves of the Colour Sensations Red, Green, Blue, and Violet, with the coefficient of friction, $k = 0.15$.

Before passing on, it must, however, be noted that according to the opto-chemical hypothesis we must imagine the decomposition products to be formed by the action of the light, independently of whether or when they are used.

* See also, for the physiological aspect of this, p. 501.

The effect of a sudden flash must be to set free a definite quantity of exciting molecules which will continue to produce sensation until their power is exhausted, or they are dispersed. This may occupy several minutes even after a momentary flash, and much longer for a more prolonged exposure to light. The phenomenon may be detected as a very brief after-effect even with light of low intensity.

Using the terms already employed:—

dx/dt is conditioned by the intensity of the illumination and the store n of exciting molecules.

de/dt represents the *positive after effect* so soon as dx/dt becomes zero, *i.e.* when exciting molecules are no longer produced.

This agrees with Fechner's theory as described by Helmholtz. And at this point it becomes necessary to take into account also the physiological elements of the visual sensation.

II. *Physiological Elements of the Visual Sensation.*

Thus far, the conditions discussed relate to one process only of the opto-chemical action, namely, the setting free of the active decomposition products which excite the retina from the bland visual substances which have no action upon it.

The other process, necessary to complete the visual effect, is physiological. It is complex, including the excitation of the sensitive elements of the retina by the active decomposition products, the transmission to the central organ of the response, and its translation into conscious sensation. Moreover, there is strong evidence of the existence of a protective mechanism whereby the intensity of the stimulus is regulated.

This physiological process is curiously distinct from the first-described opto-chemical process. The rate at which the exciting substance can be produced far exceeds that at which it can be used up. This can easily be shown by means of a photographic exposing shutter fixed in the window of the dark room. The shutter is set to give an exposure of known length, and the observer looks through it at the sun's disc reflected in the mirror of the heliostat. The positive after-image so produced lasts many times longer than the flash. I have made some attempts to establish a relation between length of flash and duration of after-image, but have had to relinquish the work for the present before getting complete data.

The store of exciting molecules set free by the action of the light is used up at a rate depending apparently on the concentration, so that it is rapid at first and dwindles down to nothing. It follows from this that during

continuous illumination the sensation of light at any instant is not due exclusively to the light falling on the eye at that instant, but includes also the remainders left over from previous illumination.

Now in the electrical stimulation of nerve, and nerve-muscle preparations, after a quite moderate strength of stimulus has been reached no further increase causes any modification of the response. This was abundantly evident in the experiments by Gotch and myself with the capillary electrometer—and, moreover, there was no sign of “fatigue” of nerve unless the excitation was excessively great. It is fair to conclude that when, under the action of light, the exciting decomposition products reach a certain concentration, no further increase adds anything to the intensity of the resultant light-sensation.

This may be far stronger than is pleasant, just as the muscular contractions during cramp may be excessively painful, but it does not seem probable that any compound produced as the result of a normal physiological process can be of such character or of such concentration as to destroy the tissues in which it originates. We should thus have a maximum limit to the possible intensity of the light-sensation—a limit independent of the particular physiological condition of the eye at the moment. Were it not for this the theory of forced vibrations would indicate that with intense and long-continued illumination the several colour-sensations must stand out more and more distinctly instead of becoming paler and tending towards white.

But there is evidence of another factor, purely physiological, which I may term the shunt-factor, whereby the strength of the sensation is governed.

I am inclined to think that this factor, manifesting itself under various conditions, affords the explanation of several quite different phenomena.

Thus Charpentier's bands may be taken as evidence that the sudden onset of a fairly bright illumination over a large surface results in a sensation of intermittent intensity. Shelford Bidwell's experiments with pigments and my own with spectral colours show that each colour-sensation acts independently of the others in this respect. Purkinje's recurrent images, especially in the striking form described by McDougall,* exhibit the same thing in connection with the positive after-effect. Some controlling mechanism is set in action whereby the positive after-effect, as it dies away, is periodically shut off like the sound in the swell box of an organ. And this action, like that of the bands of Charpentier, gives fairly rapid alternations. I take it to be a spasmodic excitation of the negative after-effect.

A similar but much slower periodicity may be observed in connection with the fusion of binocular images, especially when both are needed to complete

* ‘Journ. Psychol., 1904, vol. 1, part 1, p. 91.

some familiar outline, *e.g.* a cross. The phenomenon occurs not only with the direct image but with its positive after-effect, the waxing and waning of which was known long before the time of Thomas Young.

When making my experiments on artificial temporary colour-blindness I particularly noticed that the positive after-effect of a brilliant monochromatic light over a large retinal area showed nothing of this periodicity but died out steadily and gradually.

Putting together these facts I have suggested in my paper on "Areal Induction,"* that they indicate the existence of a protective arrangement in the retina by which the eye is shielded from the sudden effects of too strong a light. I now submit that there is sufficient evidence to identify this protective action with the negative after-effect of which it is a special case, and that the other phenomena to which I have just referred come under the same category.

The negative after-effect is so generally referred to as synonymous with fatigue that some reference to that aspect of the problem is imperative. The sensitive materials being used up and exhausted, the eye is supposed to be rendered locally less sensitive for a while. But the photo-chemical conditions indicate a state of increased activity, for if the store n is exhausted, dn/dt reaches its maximum, and during continuous steady illumination $dx/dt = dn/dt$.

But it is easy to show that during a bright summer day the quantity of sensitive material used without causing any sensation of visual fatigue greatly exceeds the consumption during the production under suitable conditions of very considerable retinal "fatigue." The explanation, therefore, must be sought among the physiological rather than the photo-chemical conditions of the problem.

We may consider a few examples. The following phenomenon is instructive, and probably familiar to most people. On a rather misty afternoon, on coming to the window, the eyes rest on a bright gap in the clouds. At first it appears too bright to look at, and the after-image is very black. But if we persist, after a few seconds the sun's disc appears sharply defined in the midst of the dazzling light.

The retina can hardly be regarded as fatigued in the sense of being exhausted and having its activities impaired, since we may continue watching until the eyes have become completely adapted to the more brilliant illumination, and further details—spots on the sun—isolated wisps of cloud in the clear space—become visible, which were at first hidden in the glare. In the subdued light of the room the store n of sensitive material had become large.

* 'Roy. Soc. Proc.,' vol. 69, p. 129.

On first glancing at the cloud gap the rate dx/dt at which exciting substances were formed was greater than that dn/dt at which sensitive material could be secreted. Accordingly, after a short time of almost painful brilliancy, the store n was reduced to zero, and a hand-to-mouth condition of things set in, during which $dx/dt = dn/dt$, *i.e.* just as much exciting substance was formed as could be furnished by the sensitive material secreted. But, during the interval, dx/dt was so far in excess of the normal that maximum sensation was produced both by the light of the clouds and by the sun itself. And it can hardly be denied that during the so-called retinal fatigue, after the details became visible, a condition of very great activity existed.* On the other hand, the sensation was undoubtedly less, and became less as the eyes got accustomed to it.

Similar phenomena may be seen in a furnace—a blinding glare in which details of flame and of molten metal with slag floating on it gradually appear—or with far less intensity of illumination in the “faces in the fire” in the hot coals of an open grate.

There is at first just the same sense of being dazzled—the same gradual perception of details, and in the end the same quiet contemplation of what has become comfortably visible, whether the experiment is made with the hot coals of the open grate or the far greater intensity of the evening sun. Yet the actual intrinsic luminosity of the hot coals is a good deal less than that of the newspaper which we read out of doors in the sunshine on a summer’s day.

The name retinal fatigue for this state is not very apt. It is a condition in which a powerful stimulus produces a reduced effect, not because the organ is in any way deteriorated or used up, but because it works best in that way. It suggests strongly the use of a shunt with a galvanometer. And if we add the idea that with the eye it takes some little time to put the shunt on, and still longer to take it off again, we have a fairly accurate description of the facts.

The condition in which a shunt factor too strong for the exciting light persists is called the negative after-effect. Thus, if S_t = the shunt-factor at time t ,

$$\frac{de/dt}{S_t} = \text{the strength of the sensation at that moment.}$$

This view of the negative after-effect agrees with the theory of Fechner on the subject, as described by Helmholtz.† I have been unable to consult

* Cf. Waller, ‘Phil. Trans.’ 1897, B, vol. 188, p. 65, note, “The retina resembles nerve with respect to its inexhaustibility.”

† Helmholtz, ‘Handbuch der Physiologischen Optik,’ 2nd ed., p. 534.

Fechner's original papers, and do not know what was his opinion on the point, but I consider that there is strong evidence that the shunt-factor is a function of the retina rather than of the brain.

The form of the curves of colour-sensation during very bright light may now be discussed. The supply dn/dt of sensitive material is limited by the rate of metabolism possible to the tissues, but the rate at which it is converted into exciting substances, dx/dt , depends on the intensity of the light. Therefore long exposure to a bright light will make the concentration of the sensitive material, and consequently also the molecular resistance, tend to a minimum. But when friction is low the amplitude of the forced vibration is slightly greater whatever be the period of the impressed vibration, and very much greater as this approaches the period natural to the resonator, so that the curve develops a very sharp central spike. This spike cannot be reproduced in the corresponding curve of colour-sensation because of the separation of the opto-chemical from the physiological functions of the eye. The active material, however concentrated, cannot do more than excite a maximal response.

But the excess of active material may excite the protective arrangement, or shunt function, to stronger action, so that the maximal response may only send through to the central organ a quite moderate sensation.

This state of things is illustrated in fig. 3, where the dotted line represents the first beginnings of artificial green-blindness, before the slit has been opened wide enough to dazzle the eye. The response is well within the limits of possible sensation, so that there is no truncation of the curve of resonance, although by the shunt-factor its ordinates are reduced to one quarter of their normal value.

It will be noted that the effect is to lessen the apparent extent of the green sensation. And this is precisely what happens. The red sensation on the one side, and the blue sensation on the other, encroach on the green. A powerful light is not required to show this. My method of testing for colour-blindness is based upon it. After looking at the *b*-lines in a spectrum of quite ordinary intensity for 30 seconds the boundary between red and green is found to have shifted from 100 to 400 Å.U. nearer the green, if the observer possesses a normal green sensation.

The height of the apex is inversely proportional to the coefficient of friction. When, therefore, this is further reduced by the action of a strong light, a stage is reached when the curve is truncated. For the height of the apex of the resonance curve is limited because in the first place dx/dt , the rate of production of the exciting substance, cannot exceed dn/dt , the rate of secretion of the sensitive visual material, and in the second place because de/dt , the

strength of the response, reaches its maximum under the action of smaller quantities of the exciting substance. Consequently the strength of the resulting sensation, when reduced by the shunt-factor, will be represented by a more or less flat-topped curve.

From various data I judge that in artificial colour-blindness of quite moderate degree, a shunt ratio of 1 : 100 before and after the exposure of the eye to light is well within the mark. I described in 1897 an experiment bearing upon this subject which seems to have escaped notice.*

When the spectrum is viewed by intermittent light of great intensity, the flash ratio being 1 : 3 or 1 : 4, as soon as the eye gets accustomed to the strong light it is seen that the continuity of the colours is gone, and that there are now visible four bands of strong colour, viz., red, green, blue, and violet, upon a pale but brightly illuminated ground. Between the intense red and the rich green is a space of a colour between yellow-ochre and raw sienna, but very pale. Between the green and the bright blue is a region of pale greenish-blue, passing into pale steel-blue. Beyond the bright blue is a pale lilac space. Farther than this cannot be seen while the red end of the spectrum is in the field, because of the overpowering intensity of the light in the neighbourhood of the yellow-green. But by shifting the prisms so that the *b*-lines come on the extreme left, while the G-line occupies the middle of the field, the region about H and K appears of a deep rich violet of great intensity, contrasting strongly with the pale lilac between it and the blue.

I suggest the following explanation. Owing to the periodic intervals of darkness during which the visual substance collects, the rate of formation of exciting substance is maximum over the whole range of the resonance. But the light is so strong that the shunt ratio is very high. Consequently, where two colour-sensations overlap, as in the yellow, we get the pale colour of the binary blend, and on either side, where only one colour-sensation is effective, the full rich tone proper to it.

The question as to how and by what mechanism the shunt function works, and where that mechanism is situated, is of the greatest interest and importance. I have already mentioned that I do not hold with those who refer it to the central organ. For one thing, it would add to the complexity of the optic nerve, as I have pointed out in my paper on "Areal Induction."† And, for another thing, it would leave the end organs in the retina unprotected. I should therefore look for the shunt mechanism in the retina itself.

If Charpentier's bands and Purkinje's recurrent images are to be regarded as due to spasmodic applications of the shunt factor, they would seem to

* 'Journ. Physiol.,' vol. 21, p. 431.

† 'Roy. Soc. Proc.,' vol. 69, p. 125.

indicate that it depends in some way upon contractile movements within the tissues. It would be quite easy to imagine an arrangement whereby a sensitive point might be dipped into or drawn out of a swarm of exciting molecules set free by the action of light on a surface close to it. The actual range necessary for such a movement to be effective would be extremely small, so that it might easily escape notice. Each retinal element would act independently of the rest, the protection from over-stimulation would obviously be complete, and spasmodic action could easily take place.

Areal induction, by which the illumination of one portion of the retina affects the surrounding areas, might result from secondary cross-connections between the retinal elements.

Note on the Laws of Weber and of Fechner.

The question arises whether the idea of a shunt factor, by which all sensations are reduced in the same ratio, is compatible with the received view that the light-sensation varies according to the logarithm of the stimulus.

Weber's law is the statement of an experimental fact, viz., that "the smallest perceptible difference of luminosity is a constant fraction of the whole intensity of the light." And this is nearly true, though, according to several observers, not accurately true, over a considerable range.

Fechner's law is on an entirely different footing. It is based on mathematical theory, and claims to establish a numerical scale of sensation:—"The intensity of the sensation varies as the logarithm of the stimulus."

If the sensation of light were a continuous function of one variable from subliminal threshold to maximum, there could be no two opinions as to the validity of Fechner's law when Weber's law is taken for granted. It is a simple, obvious, elementary application of the calculus. But the sensation of light is a function of at least three variables, viz., the production by light of the exciting substance, the stimulation by this of the end-organs, and the regulation by the shunt factor of the strength of the resulting sensation. Moreover, the perception of a difference between two sensations, which is necessarily implied in the statement of Weber's law, involves the judgments of the central organ, thus introducing a possible fourth variable. Under such conditions we are not warranted in ascribing to Fechner's law the cogency of a result obtained by the calculus as physicists use it.

The experiments of Ebbinghaus quoted by Helmholtz* go to prove that Fechner's law fails within a quite moderate range of intensities. My own experiments extending over the last three years confirm this view, and bring out, in addition, a point of considerable interest.

* Helmholtz, 'Physiol. Optik,' 2nd ed., p. 392.

I have, since 1910, in the practical classes which I have conducted for Prof. Gotch, made a considerable number of people arrange from 7 to 10 strips of white paper at distances varying from $\frac{1}{2}$ metre to 2 metres from a candle in a dark room, so that viewed from a certain point they presented a series of apparently equal gradations of luminosity. The results were very instructive, and in one respect unexpected. Most of the men repeated the experiment two or three times in order to get what they considered a good result. Almost without exception the first attempt of each person showed considerably higher values for the ratios at the two ends of the series. In the majority of cases the difference was less in subsequent experiments, but it was evident that, to the unbiassed judgment, the eye is less sensitive to differences between the brightest objects visible and also between the faintest objects visible at any one time than between those that are moderately illuminated.

Although practice reduces this divergence from Weber's law it does not do away with it. I still make the ratios at the two ends of the series higher than those near the middle of it. But with monochromatic red light any series that looks right to me under a feeble illumination looks right also in light 100 times as strong, as it should do according to Weber's law.

I am inclined therefore to accept Fechner's law with the same caution that Waller expressed in reference to the relation between strength of stimulus and the retinal currents of the frog's eye. "The curve plotted from the data comes out concave towards the abscissæ and not unlike an ordinary logarithmic curve."

If, in judging the minimum perceptible difference of brightness, we instinctively make use of the shunt function only, that would lead to something not far removed from the logarithmic law, within the range covered by the shunt.

The greater part of the experimental work connected with this paper has been done in the Physiological Laboratory, Oxford, and the expenses have been defrayed out of the Government Grant Fund.
